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An Automated Objective Technique For Constructing Tropical Cyclone Best Tracks

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ABSTRACT—A computerized objective technique has been developed to assist in the construction of tropical cyclone postanalysis tracks. The program employs linear and second-order smoothing routines to calculate storm position and intensity histories. The technique is general in nature and can incorporate fix information from any of the usual tropical cyclone reconnaissance platforms. It is currently undergoing evaluation at the Fleet Weather Central/Joint Typhoon Warning Center on Guam, Marianas Islands, as an aid in the development of best tracks for the western North Pacific Ocean and Bay of Bengal tropical cyclones.

1. INTRODUCTION

The reliability of tropical cyclone climatology depends heavily on the validity of the techniques used by the analyst in the construction of best tracks (position/intensity histories). Changes in reconnaissance platforms and procedures, postanalysis personnel, and forecast verification schemes have caused techniques to vary over the years, creating questionable trends in climatological data. Brand (1972) cited examples of such trends in the typhoon climatology maintained by the Fleet Weather Central/Joint Typhoon Warning Center (FWC/JTWC) on Guam, and Cry (1965) described similar problems in the Atlantic Ocean. Since reliable data are essential for progress in tropical cyclone research, it is desirable that spurious climatological trends be reduced. It was with this goal in mind that an objective technique for the construction of tropical cyclone best tracks was developed.

In the past, fix information from various reconnaissance sources had to be analyzed subjectively to produce a smoothed postanalysis best track. Each piece of data was evaluated with respect to the accuracy of the fix platform and consistency to other positioning data to determine the final smoothed track. Since position and intensity data are frequently inconsistent and there are often 100 or more fixes per storm, evaluation of the data can be a formidable undertaking. The computer seems well suited to the task.

The objective best track computer program reads tropical cyclone fix information from punch cards. Each card contains a fix position and time, and most include intensity information. These data are weighed and grouped based on preassigned weighting factors. Latitude, longitude, intensity, and accuracy time functions are then calculated using linear and second-order smoothing routines. The weighting factor assigned to each fix is based on the historical accuracy of its reconnaissance platform. This factor largely determines the influence a fix will have on the final best track of the storm. The weighting factor values currently in use are tentative and based on 1971 and 1972 error statistics for the various platforms. They are undergoing continuous evaluation and refinement.

This technique is first described in general terms without reference to specific fix sources or weighting factors. The use of the technique in the construction of best tracks at FWC/JTWC is then detailed. The symbols used in this paper are defined in table 1 and in the text. The relationship among the various parameters and values assigned at various stages in the development of the objective best track is summarized in table 2.

2. GENERAL DESCRIPTION OF THE BEST-TRACK PROGRAM

Position History Routine

The program initially divides the time domain as defined by T_1 and T_2 (the best track start and end times) into nn intervals as depicted in figure 1. Intervals 2 through $nn-1$ are integral multiples of 3 hr such that each contains at least one fix. Intervals 1 and nn are bounded on the low and high side, respectively, by the annual zero point of the Julian calendar. To eliminate unwanted short-term movements, we reduced the set of n individual fixes to a smaller set of nn group points. Each group point i is assigned a time (TB_i), longitude (XB_i), latitude (YB_i), and accuracy (AB_i) as derived from a weighted combination of the fixes falling within a time interval according to

$$TB_i=\left(\sum_{j=l}^{m}\frac{TX_j}{AX_j}\right)\left(\sum_{j=l}^{m}\frac{1}{AX_j}\right)^{-1}, \tag{1}$$

$$XB_i=\left(\sum_{j=l}^{m}\frac{XX_j}{AX_j}\right)\left(\sum_{j=l}^{m}\frac{1}{AX_j}\right)^{-1}, \tag{2}$$

$$YB_i=\left(\sum_{j=l}^{m}\frac{YX_j}{AX_j}\right)\left(\sum_{j=l}^{m}\frac{1}{AX_j}\right)^{-1}, \tag{3}$$

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TABLE 1.—*Symbols and their meanings*

a	Position accuracy in nautical miles—represents a 75-percent confidence limit on the position error from a particular category fix and is assumed symmetric in longitude and latitude
D_1	TB_i-TB_{i-1}
D_2	$TB_{i+1}-TB_i$
H_{700}	The 700-mb height in meters at the center of a tropical cyclone
k	Number of intensity estimates from a particular fix
mm	Number of final best track points
n	Number of fixes for a particular storm
nn	Number of group points for a particular storm
P	Minimum sea-level pressure in millibars
r	Percent wind error or reliability—represents a 75-percent confidence limit on the wind error as a percent of true value
RD_j	The r associated with a particular WD_j
t	Time in Julian hours and tenths since 0000 GMT on January 1
T_1	Best track start time
T_2	Best track end time
w	Maximum sustained surface wind in knots
WD_j	The w estimate based on a particular type of intensity
W_{fl}	Flight level wind in knots
x	Longitude
x_{chg}	Five group point weighted average corner cutting displacement in x
y	Latitude
y_{chg}	Five group point weighted average corner cutting displacement in y
β	Adjusted point in the linear smoothing routine
δ	Intermediate point in the second-order smoothing routine at TB_{i+3}
γ	Intermediate point in the second-order smoothing routine at TB_{i+1}
λ	Intermediate point in the linear smoothing routine

and

$$AB_i=(m-l+1)\left(\sum_{j=l}^{m}\frac{1}{AX_j}\right)^{-1} \tag{4}$$

where l is the first and m is the last fix falling in the interval.

The set of group points now undergoes four linear smoothings/accuracy adjustments. Latitude and longitude are considered separately as a function of time. Each group point i ($i=2$, $nn-1$) is adjusted in reference to adjacent group points $i-1$ and $i+1$ as shown in figure 2. First, an intermediate point λ is determined on the straight line connecting $i-1$ and $i+1$ such that $t_\lambda=TB_i$. The position and accuracy parameters of this intermediate point are given by

$$x_\lambda=(D_2XB_{i-1}+D_1XB_{i+1})(D_1+D_2)^{-1}, \tag{5}$$

$$y_\lambda=(D_2YB_{i-1}+D_1YB_{i+1})(D_1+D_2)^{-1}, \tag{6}$$

and

$$a_\lambda=(D_2AB_{i-1}+D_1AB_{i+1})(D_1+D_2)^{-1} \tag{7}$$

where D_1 and D_2 are the time differences, respectively, between point i and points $i-1$ and $i+1$. Now, group point i is moved in reference to the intermediate point λ to yield an adjusted group point β such that

$$x_\beta=(a_\lambda XB_i+AB_ix_\lambda)(a_\lambda+AB_i)^{-1}, \tag{8}$$

$$y_\beta=(a_\lambda YB_i+AB_iy_\lambda)(a_\lambda+AB_i)^{-1}, \tag{9}$$

$$a_\beta=2a_\lambda AB_i(a_\lambda+AB_i)^{-1}, \tag{10}$$

and

$$t_\beta=TB_i. \tag{11}$$

A check is made to determine whether group point i will be moved out of its accuracy circle, defined by the radius (AB_i) within which the actual position of the storm will fall at the 75-percent confidence level. This radius is determined by the accuracy weighting factors (AX_j) assigned to the fixes used in deriving the group point. If the group point would be adjusted beyond the accuracy circle, it is not moved, but the radius is increased 40 percent.[3] If the group point would not be moved outside the accuracy circle, it is moved to the adjusted position β so that $XB_i=x_\beta$, $YB_i=y_\beta$, and $AB_i=a_\beta$. Thus on each smoothing cycle, group points that have greater scatter than expected are not smoothed, but their accuracy radii are enlarged so that their influence will decrease and the probability of their being adjusted will increase in the next cycle. Since the accuracy radius of an ignored group point will increase 2.7 times through three cycles, it is highly probable that all group points willbe smoothed at least once during the four cycles. This routine enables the program to incorporate fixes of less than the expected accuracy but which still provide useful information.

After the linear smoothing, the set of group points (excluding $i=1$ and $i=nn$) undergoes two cycles of second-order smoothing. This process considers five group points at a time, adjusting points $i+1$ and $i+3$ in reference to a second-order polynomial through i, $i+2$, and $i+4$ (fig. 3). Intermediate points γ and δ are determined on the polynomial such that $t_\gamma=TB_{i+1}$ and $t_\delta=TB_{i+3}$. Group points $i+1$ and $i+3$ are moved one-fourth[4] of the distance (dist) to points γ and δ. This process is accomplished for both longitude and latitude, giving new values for XB_{i+1}, YB_{i+1}, XB_{i+3}, and YB_{i+3}. No accuracy weighting adjustment takes place during the second-order smoothing cycles.

After completion of the second-order smoothing, the position history (as defined by the collection of group points) is adjusted to correct any corner cutting that may have been introduced in the smoothing cycles. Corner cutting may result from linear smoothing of the points on a curve; the curve tends to straighten or be displaced toward the center of curvature. This routine also helps correct inaccuracies that may be introduced by a poor fit of the polynomial used in second-order smoothing. The points are considered in groups of five where group point $i+2$ is adjusted based on the accumulated smoothing displacement experienced by i, $i+1$, $i+2$, $i+3$, and

[3] AB_i is increased by 40 percent so that, over four cycles, the probability that point i lies outside a circle with radius AB_i is less than 0.010, assuming a normal circular distribution for the population of fix positions about the verifying point for each fix category.

[4] There is no rigorous basis for the selection of one-fourth; however, since second-order smoothing provides the final adjustment, a large fraction would be inappropriate.

TABLE 2.—*Relationship among various parameters and the values assigned at various stages in the development of the objective best track*

Parameters	t	x	y	w	a	r	
Value at ith fix within a set of tropical cyclone fixes	TX_i	XX_i	YX_i	WX_i	AX_i	RX_i	$i=1, n$
Value at ith point within a set of derived group points	TB_i	XB_i	YB_i	WB_i	AB_i	RB_i	$i=1, nn$; $nn<n$
Value at ith point within a set of final best track points	TF_i	XF_i	YF_i	WF_i	AF_i	RF_i	$i=1, mm$

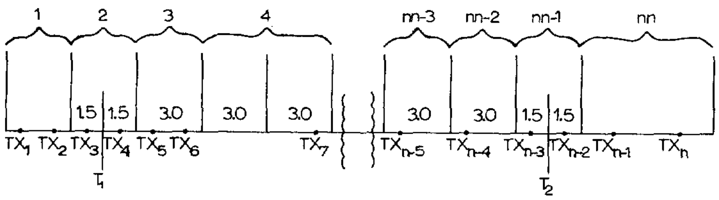

FIGURE 1.—Division of the time domain. The time domain as defined by T_1 and T_2 is divided into nn intervals. Intervals 1 and nn meet at the annual zero point of the Julian calendar.

$i+4$ according to

$$XB_{i+2} \leftarrow (XB_{i+2} - x_{chg}) \tag{12}$$

and

$$YB_{i+2} \leftarrow (YB_{i+2} - y_{chg}) \tag{13}$$

where

$$x_{chg} = \left(\sum_{j=i}^{i+4} \frac{DX_j}{AB_j}\right)\left(\sum_{j=i}^{i+4} \frac{1}{AB_j}\right)^{-1} \tag{14}$$

and

$$y_{chg} = \left(\sum_{j=i}^{i+4} \frac{DY_j}{AB_j}\right)\left(\sum_{j=i}^{i+4} \frac{1}{AB_j}\right)^{-1}. \tag{15}$$

here,

$$DX_i = XB_i \text{ (after smoothing) } - XB_i \text{(before smoothing)} \tag{16}$$

and

$$DY_i = YB_i \text{ (after smoothing) } - YB_i \text{(before smoothing)}. \tag{17}$$

For any portion of the track, a smoothing displacement biased in one direction will yield values of x_{chg} and y_{chg} significantly different from zero (fig. 4). The accuracies must be considered to prevent the large smoothing displacement of bad group points from controlling the sign of x_{chg} and y_{chg}.

After the corner-cutting correction, the program determines latitude, longitude, and position accuracy values corresponding to the set of desired best track times (0000 GMT plus every 3 hr) using second-order interpolation. The arrays TF_i, YF_i, XF_i, and AF_i constitute the best track times, positions, and accuracies and are the final result of the objective position history routine.

Intensity History Routine

The intensity history routine closely parallels the position history routine. However, the data used cannot

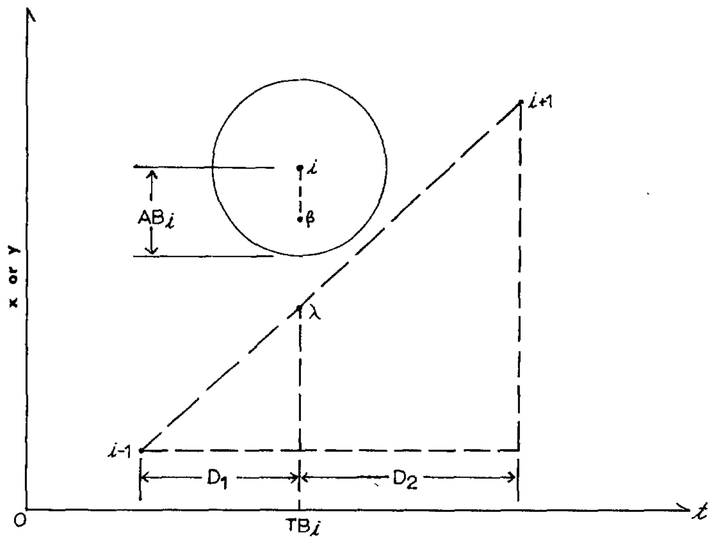

FIGURE 2.—Linear smoothing group point adjustment. Group point i is adjusted based on a straight line through $i+1$ and $i-1$.

always be read directly from the fix data cards. The initial intensity and reliability values for a particular fix (WX_i and RX_i) frequently must be constructed from several different intensity information types. Each type yields a maximum sustained surface wind estimate (WD_j) and an associated wind reliability (RD_j). For example, WD_j can sometimes be read directly from the fix card, as in the case of an intensity estimate based on satellite data. It frequently, however, must be calculated using relationships with other measured parameters. An aircraft penetration into a typhoon's eye usually yields four estimates of maximum sustained surface wind: one resulting from estimated surface wind based on the observed sea state, another based on measured flight level wind, and two related to the minimum central pressure at sea level. Each of these estimates (WD_j) is assigned a reliability (RD_j), depending on its source. WX_i and RX_i are then determined such that

$$WX_i = \left(\sum_{j=1}^{k} \frac{WD_j}{RD_j}\right)\left(\sum_{j=1}^{k} \frac{1}{RD_j}\right)^{-1} \tag{18}$$

and

$$RX_i = (k)\left(\sum_{j=1}^{k} \frac{1}{RD_j}\right)^{-1} \tag{19}$$

where k is the number of intensity estimates from a particular fix.

Some fixes (e.g., radar positions) lack intensity param-

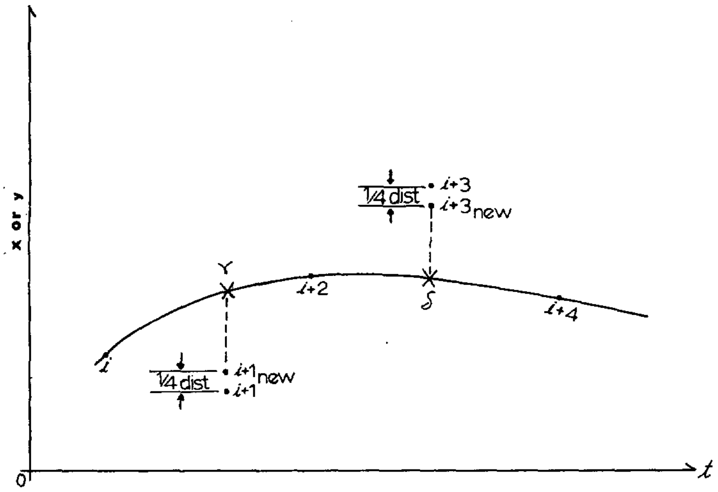

FIGURE 3.—Second-order smoothing group point adjustment. Group points $i+1$ and $i+3$ are adjusted based on a second-order curve through i, $i+2$, and $i+4$.

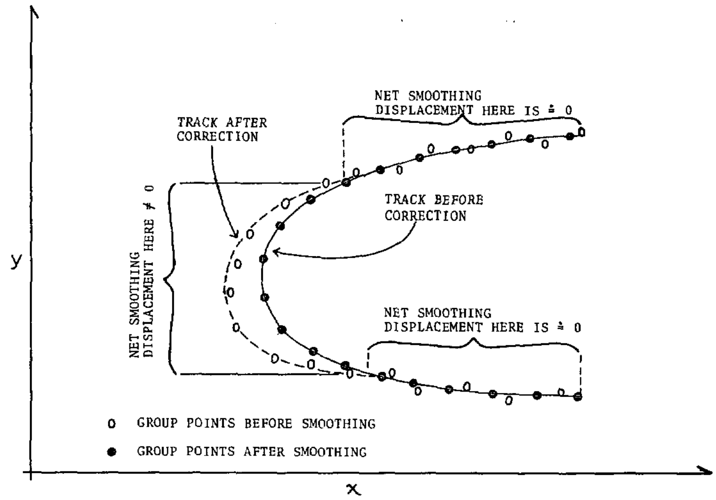

FIGURE 4.—Corner-cutting correction as applied to a hypothetical track.

eters altogether, leaving WX_i and RX_i unfilled. In this case, the bogus value −99 is assigned as the intensity estimate during the first pass through the data. After the other WX_i and RX_i values have been determined, a second pass is made to replace the bogus values with appropriate wind and reliability values. For each fix assigned a bogus WX_i and RX_i, a search is made back in time until a fix having nonbogus values is found. The bogus WX_i and RX_i are then replaced with these values. If the search back in time is unsuccessful, a search is conducted forward toward T_2 until a valid WX_i is located. The bogus values are than replaced as before.

This procedure can be improved by going forward and backward in every case and then interpolating. This feature will be incorpoarted in later versions of the technique. However, the present method for determination of WX_i and RX_i is satisfactory as long as fixes with intensity parameters are fairly numerous and evenly distributed in time.

The program treats the WX_i and RX_i arrays in the same manner as the XX_i, YX_i, and AX_i, arrays through the grouping, smoothing, corner cutting, and time interpolation routines. This treatment produces the final intensity arrays WF_i and RF_i. Thus the objective best track output consists of storm position (XF_i and YF_i), position accuracy (AF_i), maximum sustained surface wind (WF_i), and wind reliability (RF_i), all at intervals (TF_i). In addition, 3-hr and 6-hr headings and speeds are calculated and printed between the best track points. Finally, the output contains the mean and standard deviation of AF_i and RF_i to aid in the comparison of best tracks.

3. APPLICATION OF THE OBJECTIVE BEST TRACK PROGRAM

Position History Routine

To determine values of the accuracy weighting factor AX_j (the accuracy radius at the 75-percent confidence level for a particular fix) used in eq (1)–(4), one must classify the fixes according to the accuracy of the source. Tropical cyclone fix sources include weather reconnaissance aircraft, land or ship radar, weather satellite data, synoptic analyses, and special reports from stations (land, island, and ship) experiencing eye passage.

The group of fix sources is broken down into 27 specific categories for which accuracy weighting factors are designated. Reconnaissance aircraft fixes at various levels account for four of the categories. Land, ship, and aircraft radar reports, synoptic chart positions, and the special reports described previously constitute seven more. The remaining 16 categories are devoted to satellite fix data.

Accuracy weighting factors are allotted to each automatic picture transmission (APT)-type satellite fix according to the current intensity (CI) number assigned using the new National Environmental Satellite Service (NESS) classification system (Dvorak 1973). Well-developed storms are considered to be fixed more accurrately than poorly developed ones. The U.S. Air Force's very high resolution weather satellite pictures [Data Acquisition and Processing Program (DAPP) data] provide much valuable fix information. The accuracy weighting factor is assigned to a DAPP fix according to its position code number (PCN). The PCN ranges from one (most accurate) to six and depends on gridding accuracy and stage of storm development.

As stated in the introduction, the actual weighting factors in use are tentative and are undergoing constant refinement. They currently range from 18 n.mi. for a 700 mb level reconnaissance aircraft fix to 150 n.mi. for a CI number 1.0 APT satellite fix.

The program is also designed to accommodate fixes from sources that cannot be assigned to any of the 27 categories, in which case a subjective accuracy value is assigned by the analyst. In addition, the designated accuracy for any category can be replaced by a more realistic value if the analyst knows a particular fix to be significantly more or less accurate than the value assigned to that fix platform.

TABLE 3.—*Type of intensity information (from various sources) with the related wind and wind reliability estimates*

Type (j)	Source	WD_j	RD_j	Remarks
1	ESSA* 8, 9, NOAA 2	Estimated w	22	The w estimated using the NESS system
1	DAPP	Estimated w	20	The w estimated using the NESS system
1	Land station	Reported w	20	Station <30 n.mi. from the storm center
1	Ship report	Reported w	20	Ship <30 n.mi. from the storm center
1	Synoptic analysis	Estimated w	20	The 3+ stations <60 n.mi. from the center
1	Recon† aircraft	Estimated w	20	The w estimated from the sea state
2	Recon aircraft	Eq (20)	20	P in eq (20) determined by eq (21)
3	Recon aircraft	Eq (20)	18	P, minimum reported SLP‡
3	Land station	Eq (20)	18	P, minimum reported SLP
3	Ship report	Eq (20)	18	P, minimum reported SLP
3	Synoptic analysis	Eq (20)	18	P subjectively derived
4	Recon aircraft	Eq (22)	16	W_{fl}, flight-level wind

*Environmental Science Services Administration (satellites)
†Reconnaissance
‡Sea-level pressure

Once the position fix sources and categories have been determined and the accuracy weighting factors assigned, the program proceeds with the position history routine as described previously.

Intensity History Routine

An accurate determination of maximum sustained surface wind is probably the most difficult problem faced by the analyst. As previously noted, some fix sources provide no intensity information. Observers in reconnaissance aircraft measure winds in only a small part of the storm, which may not include the most intense region. Satellites sample the entire storm, but intensity estimates are based on the organization of the cloud structure, not direct measurement. Land stations may not report the maximum winds in a storm because of location, topography, or instrument failure. Thus an objective best track technique must consider all available information (measured or derived) to arrive at a final intensity estimate.

The program first determines the maximum sustained surface wind (WX_i) to be assigned to a particular fix. Four types of maximum intensity information are conconsidered: (1) surface wind data, (2) 700 mb height data, (3) sea level pressure data, and (4) flight-level wind data. An aircraft fix may include data of all four types, and a satellite fix will include information of type 1 only.

A complete list of the data types is given in table 3, which relates each type of intensity information with its source, the associated maximum sustained surface wind (WD_j), and reliability (RD_j). The following equations are cited in table 3:

$$WD_j=13.4\ (1010-P)^{1/2}, \tag{20}$$

$$P=645+0.115\ (H_{700}), \tag{21}$$

and

$$WD_j=1.10\times W_{fl}. \tag{22}$$

Equation (20) is from Takahashi (1939). Equation (21) was developed by Jordan (1957), and eq (22) was derived empirically in FWC/JTWC (1972).

The reliabilities of the wind estimates r (±percent) of the various platforms are given in table 3 under RD_j. These values are listed only for illustrative purposes. Like the weighted position accuracies, they are undergoing evaluation and refinement. It should be noted, however, that all values fall close to ±20 percent. Thus at this time, there is little discrimination among intensity data sources. This is particularly true upon consideration of the weighting and smoothing processes, which tend to further reduce the differences.

After WD_j and RD_j are determined for a fix, the values are substituted into eq (18) and (19) to yield a final wind (WX_i) and reliability (RX_i) estimate for the fix.

To further illustrate the computational process, consider the following example using hypothetical data from a weather reconnaissance aircraft:

$$w=55\text{ kt},$$

$$W_{fl}=70\text{ kt},$$

$$P=978\text{ mb},$$

and

$$H_{700}=2860\text{ m}.$$

Therefore,

$$WD_1=w=55\text{ kt} \qquad (RD_1=20),$$

$$WD_2=13.4\ (1010-974)^{1/2}=80\text{ kt}$$

$$\text{where } P=974\text{ mb by eq (21)} \qquad (RD_2=20),$$

$$WD_3=13.4\ (1010-978)^{1/2}=70\text{ kt} \qquad (RD_3=18),$$

and

$$WD_4=(1.10)\ (70)=77\text{ kt} \qquad (RD_4=16).$$

Substituting into eq (18) and (19) with $k=4$ yields

$$WX_i=\left(\frac{\frac{55}{20}+\frac{80}{20}+\frac{70}{18}+\frac{77}{16}}{\frac{1}{20}+\frac{1}{20}+\frac{1}{18}+\frac{1}{16}}\right)=\frac{15.35}{0.22}=70\text{ kt}$$

and

$$RX_i = \frac{4.00}{0.22} = 18.$$

Now consider a hypothetical DAPP satellite fix that yields only one type of wind information:

$$w = 65 \text{ kt}.$$

Therefore,

$$WD_1 = w = 65 \text{ kt} \qquad (RD_1 = 20).$$

The terms WD_2, WD_3, WD_4, RD_2, RD_3, and RD_4 are not obtainable from this fix ($k=1$).
Substitution into eq (18) and (19) yields identical values:

$$WX_i = \left(\frac{65}{20}\right)\left(\frac{20}{1}\right) = 65 \text{ kt}$$

and

$$RX_i = (1)\left(\frac{20}{1}\right) = 20.$$

Similar exercises can be performed for land or ship reports and synoptic analyses. As stated previously, those fixes that contain no intensity information ($k=0$) are assigned $WX_i = -99$ and $RX_i = -99$ on the initial pass through the data. After the WX_i and RX_i arrays have been filled, the program proceeds with the intensity history routine as previously described.

4. CONCLUSIONS

The computer-produced best tracks used for guidance at FWC/JTWC during 1972 agree reasonably with the final subjective best tracks published in FWC/JTWC (1973). Nevertheless, the position weighting factor and intensity accuracy values are preliminary, and conclusions on the goodness of the tracks cannot be drawn until these values have been refined on a larger data base and the program has been tested over several years.

The ability of the technique, however, to eliminate analyst bias (producing only one track for a particular set of data) is significant and represents an important step toward meeting the goal advanced by the authors. With the advent of new reconnaissance capabilities (such as high resolution satellite data) and continuing changes in aircraft, land radar, and other fix sources, the analyst must construct the best track based on the latest accuracy statistics without injecting personal bias. Hopefully, an objective reference best track will help in this construction.

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